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TANDEM MIRROR AND FIELD-REVERSED MIRROR EXPERIMENTS*

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ABSTRACT

Multiple-mirror systems offer significant enhancement of the power balance above that attainable from a conventional single-cell mirror reactor. Several multiple-mirror configurations are under experimental investigation: the tandem mirror, the high-density multiple-mirror, and the field-reversed mirror. This paper is largely devoted to tandem mirror and field-reversed mirror experiments at the Lawrence Livermore Laboratory (LLL), and briefly summarizes results of experiments in which field-reversal has been achieved. In the tandem experiment, high-energy, high-density plasmas (nearly identical to 2XIIB plasmas) are located at each end of a solenoid where plasma ions are electrostatically confined by the high positive potentials arising in the "end plug" plasmas. End plug ions are magnetically confined, and electrons are electrostatically confined by the overall positive potential of the system. The field-reversed mirror reactor consists of several small field-reversed mirror plasmas linked together for economic reasons. In the LLL Beta II experiment, generation of a field-reversed plasma ring will be investigated using a high-energy plasma gun with a transverse radial magnetic field. This plasma will be further heated and sustained by injection of intense, high-energy neutral beams.

Key words: magnetic mirror; thermonuclear reactors; fusion; tandem mirror; field-reversed; θ-pinch; multiple mirrors.

INTRODUCTION

Tandem mirrors and field-reversed mirrors, both of which operate with open-ended magnetic mirror coils and at high beta, offer a number of advantages over a conventional single-cell mirror reactor; e.g., both reactor concepts could produce modest power output and retain the desirable engineering construction and maintenance features characteristic of the open-ended magnetic design. Due to the attractive features of these systems, there are a number of experiments underway to investigate and demonstrate the confinement properties of such mirror

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configurations. There are other attractive systems in mirror geometry such as the high-density, multiple mirrors discussed by Ryutov (1978). Results of plasma confinement experiments in single-cell mirrors that are the stepping stone for these improved experiments are reviewed in our other paper at this meeting.

Reactor design studies have been carried out at Lawrence Livermore Laboratory (LLL) for both the tandem mirror (Carlson and co-workers, 1978) and field-reversed mirror (Moir and co-workers, 1977). Table 1 gives preliminary parameters for designs currently under study. Other groups have also carried out tandem mirror and field-reversed mirror reactor designs to further illustrate reactor options.

TABLE 1 Examples of Tandem Mirror and Field-Reversed Mirror Reactor Designs

	Tandem mirror*	Single-cell reversed mirror†
B_{max} (T)	12	4.1
E_{inj} (keV)	200	200
$P_{neutral\ beam}$ (MW)	10	3.6
$P_{electron\ heating}$ (MW)	57	0
P_{fusion} (MW)	1500	20
Length (m)	50	2.0
Q	23	5.5

*Carlson and co-workers (1978).
†Moir and co-workers (1977).

TANDEM MIRROR CONCEPT

The tandem mirror configuration suggested by Dimov, Zakaidakov, and Kishinevskii (1976) and by Fowler and Logan (1977) utilizes a number of demonstrated mirror physics principles. Figure 1 shows the essential parts of a tandem mirror machine. Two single-cell mirror machines are placed at the ends of a longer solenoid. The mirror machine end plugs provide a minimum-B magnetic field that contains a high-temperature plasma. Since hot ions injected by neutral beams are better confined than the electrons, the end plugs develop a positive electric potential that confines the electrons. This positive end-plug potential, together with the high magnetic mirror ratio, confines the solenoid ions (which are created by ionization of gas feed into the solenoid).

In the tandem mirror reactor, most of the fusion power will be produced in the solenoid. Despite the fact that the end plugs are not efficient power producers, the overall Q of the tandem system can be high because the solenoid volume V_c can be much larger than the end plug volume V_p; that is,

$$Q = \frac{P_n V_c}{P_c V_c + 2P_p V_p} \quad , \tag{1}$$

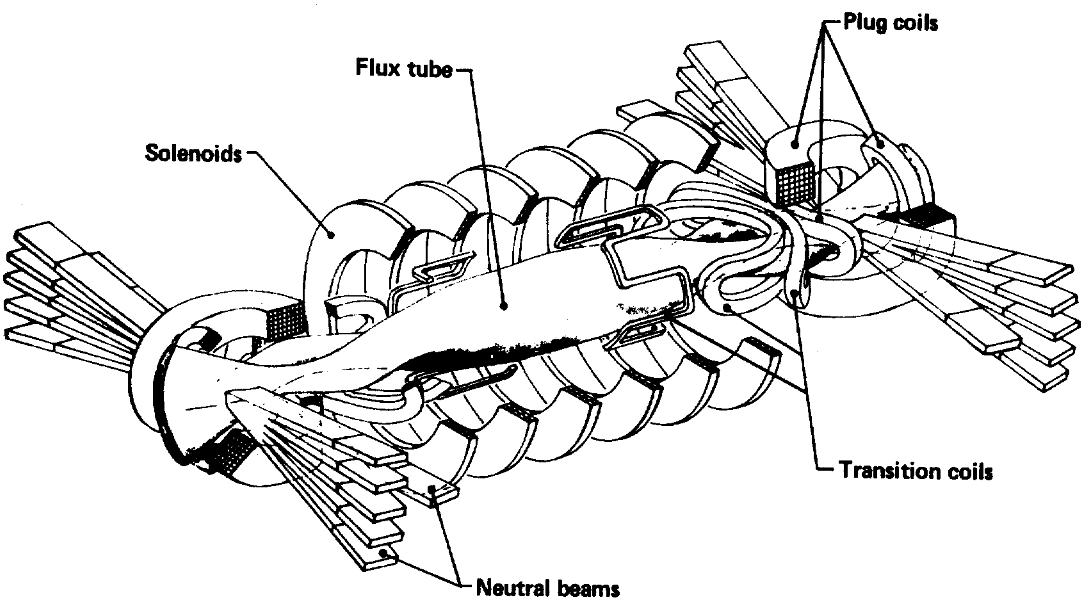

Fig. 1. Artist's drawing of TMX illustrates essential features of tandem mirror machine.

where P_c and P_p are the externally supplied power per unit volume necessary to sustain the central cell and end plugs, respectively, and P_n is the thermonuclear power per unit volume generated in the solenoid.

The geometry of the tandem mirror is sketched in Fig. 2. High-energy neutral beams maintain dense mirror plasmas in the end cells. The ions lost from the central solenoid are replaced by injection of low-energy neutral beams, gas, or pellets, which are ionized and heated by the hot electrons. The electrons are in turn heated by the energetic ions in the plugs, and possibly by additional auxiliary heating such as electron cyclotron resonance heating (ECRH). Thus, the system is characterized by $E_p > T_e > T_c$, where E_p is the average ion energy of the plug, T_e is the electron temperature (which is the same in both plugs and solenoid), and T_c is the ion temperature in the central cell.

If the density in the plugs n_p is greater than that in the solenoid n_c, the requirement of quasi-neutrality establishes a potential difference ϕ_c between the two regions. For a Boltzmann distribution of electrons, ϕ_c is given by

$$\phi_c = T_e \ln \frac{n_p}{n_c} \quad . \tag{2}$$

Central-cell ions with energy less than ϕ_c are confined in this axial potential well for the time τ_c required for them to diffuse upward in energy above the barrier height. For $\phi_c \gtrsim 2T_c$, τ_c is given by Pastukhov (1974) as

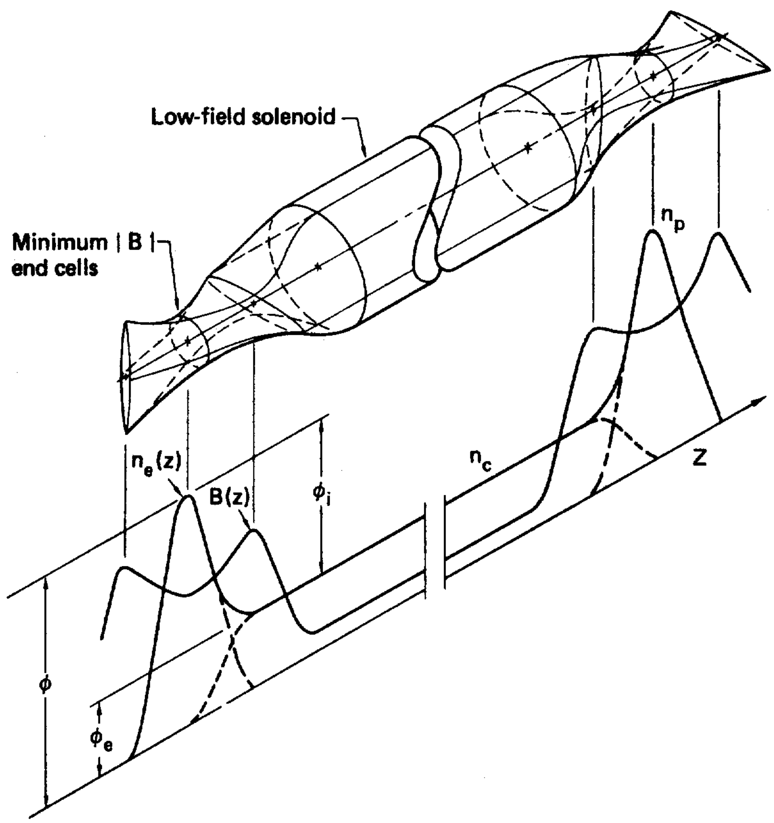

Fig. 2. Tandem mirrors with ambipolar barriers at the ends.

$$\tau_c = \tau_{ii}\ g(R) \left(\frac{\phi_c}{T_c}\right) \exp\left(\frac{\phi_c}{T_c}\right) \quad , \tag{3}$$

where τ_{ii} is the ion-ion collision time, and $g(R) = \sqrt{\pi}(2R + 1)\ \ln(4R + 2)/4R$ is a slow function of the central-cell mirror ratio $R = B(\text{mirror})/B(\text{solenoid})$. Substituting Eq. (2) into Eq. (3) gives

$$\tau_c = \tau_{ii}\ g(R) \left(\frac{T_e}{T_c}\right) \ln\left(\frac{n_p}{n_c}\right) \left(\frac{n_p}{n_c}\right)^{T_e/T_c} \quad . \tag{4}$$

Provided $T_e \gtrsim T_c$, a properly chosen injection flux of ions into the solenoid and the plugs (which are subject to conventional mirror confinement) will maintain an arbitrary density ratio $n_p/n_c > 1$, so that any enhancement of τ_c over τ_{ii} is feasible. The temperature inequality $T_e \gtrsim T_c$ is important to minimize the density ratio required for adequate electrostatic confinement of central-cell ions. Thus, it is advantageous to use heating methods that preferentially heat electrons.

Electrons are confined by a net positive potential ϕ_e relative to ground; this potential adjusts to a value equalizing the electron losses with the combined ion loss from the plugs and the solenoid. Under most operating conditions, ϕ_e exceeds ϕ_c by a factor of 2 to 3.

Because of the enhancement of the confinement time over τ_{ii} given by Eqs. (3) or (4), the Q of a tandem mirror reactor [Eq. (1)] can considerably exceed unity.

Tandem Mirror Experiments

There are four tandem mirror experiments under way (see Table 2). Gamma 6 at Tsukuba University in Japan (Miyoshi and co-workers, 1978; Yatsu and co-workers, 1979) began operation in the spring of 1978. Experiments on the Tandem Mirror Experiment (TMX) at LLL (Coensgen, 1977) began in July 1979. Phaedrus at the University of Wisconsin (Mai, Kesner, and Post, 1977) and AMBAL-1 at Novosibirsk (Ryutov, 1978) are under construction. In this paper, we review results from the operating tandem mirror experiments Gamma 6 and TMX.

Gamma 6 Tandem Mirror Experiment

The Gamma 6 experiment has given early indication of the promise of tandem mirror geometry. The parameters of Gamma 6 are summarized in Table 2 and schematic diagrams are shown in Fig. 3 of the experimental apparatus and in Fig. 4 of the plasma. Gamma 6 includes several heating systems, neutral-beam injection (NBI), radio frequency (rf) (Miyoshi and co-workers, 1978), and relativistic electron beam (REB) (Kawabe and co-workers, 1978). In order to obtain early physics results, Gamma 6 was built without solenoid transition coils. Consequently, the solenoid is elliptical and the end plugs are not rotated 90° relative to one another. This introduces limitations (Ryutov and Stupakov, 1978) on solenoid confinement that will not be present in the proposed next experiment, Gamma 10.

The first results from Gamma 6 showed that a macroscopically stable density distribution could be created in the tandem mirror magnetic field configuration. Using Langmuir probes, the Gamma 6 group has shown the formation of an ambipolar plug potential that, as shown in Fig. 5, increased in magnitude with neutral-beam injection (Miyoshi and co-workers, 1978). In more recent Gamma 6 experiments, measurements showed that the measured potential difference between the end plug and central cell was in agreement with calculations based on the fundamental relation $\phi = T_e \ln(n_p/n_c)$ given in Eq. (2). The calculations take account of the time and space dependence of electron temperature. Most recently, 2-keV electron energies have been achieved using REB heating.

TMX Tandem Mirror Experiment

This section describes the TMX device, the experiments that are under way, and reports the first results. A theoretical model for TMX operation has been published (Cohen, 1979), and other physics issues related to tandem mirror confinement have been summarized (Baldwin and co-workers, 1978; Kishinevsky and co-workers, 1978).

TABLE 2 Summary of Design Parameters of Tandem Mirror Experiments in Operation or Construction

	Gamma 6	TMX	Phaedrus	AMBAL-1
Plug:				
B_0 (kG)	4	10	2	12
B_{mirror} (kG)	10	20		
R_p (cm)	4	10	7	12
L_m mirror-mirror (cm)		75	90	
Heating method	Beam,RF,REB	Beam	ICRF	Beam
Heating power (MW)	0.5	9	0.1	1.0
Duration (ms)	2.5	25	1	
n (cm^{-3})	5×10^{13}	5×10^{13}	5×10^{12}	3×10^{13}
W_i (keV)	0.4-10	26	2	20
T_e (eV)	20-2000	200	40	1000
Solenoid:				
B (kG)	1.5	0.5-2.0	0.5	2
$L_{plug-to-plug}$ (cm)	315	640	390	
R_p (cm)	2 × 20	30	14	30
n (cm^{-3})	1.0×10^{13}	1×10^{13}	2×10^{12}	1×10^{13}
W_i (eV)		80	15	500-1000
T_e (eV)	300	200		

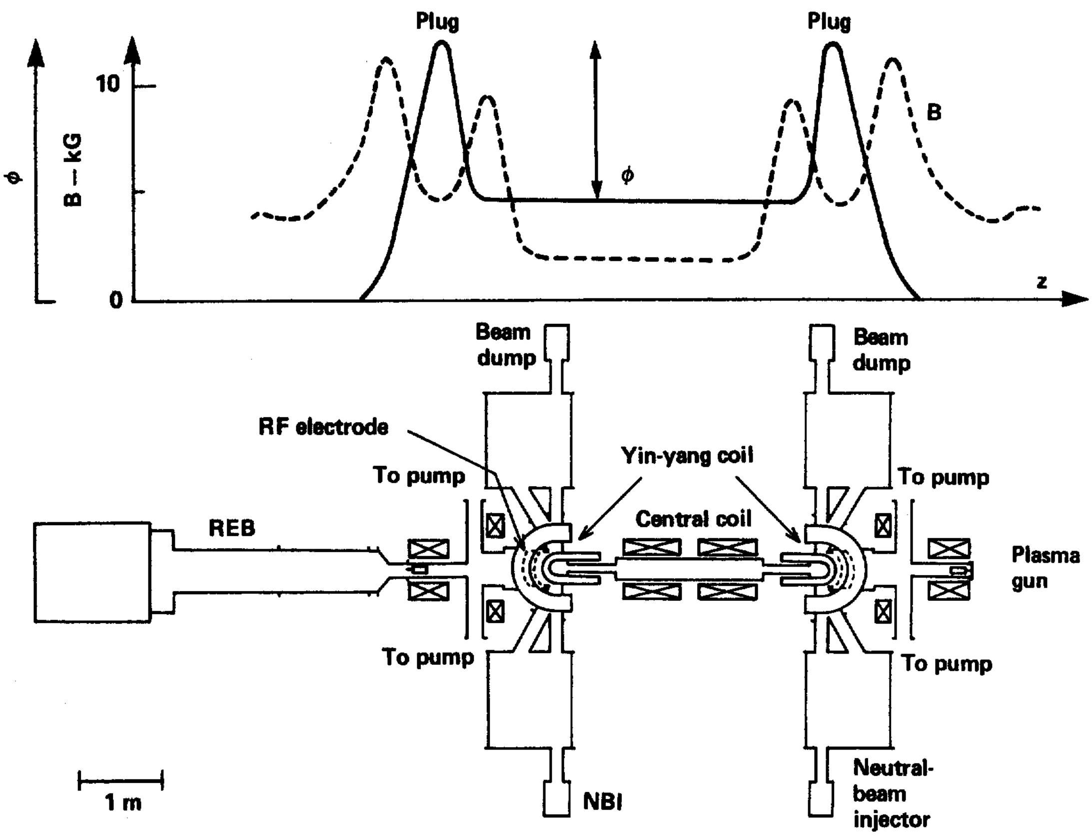

Fig. 3. Schematic diagram of Gamma 6 experiment (Miyoshi and co-workers, 1978).

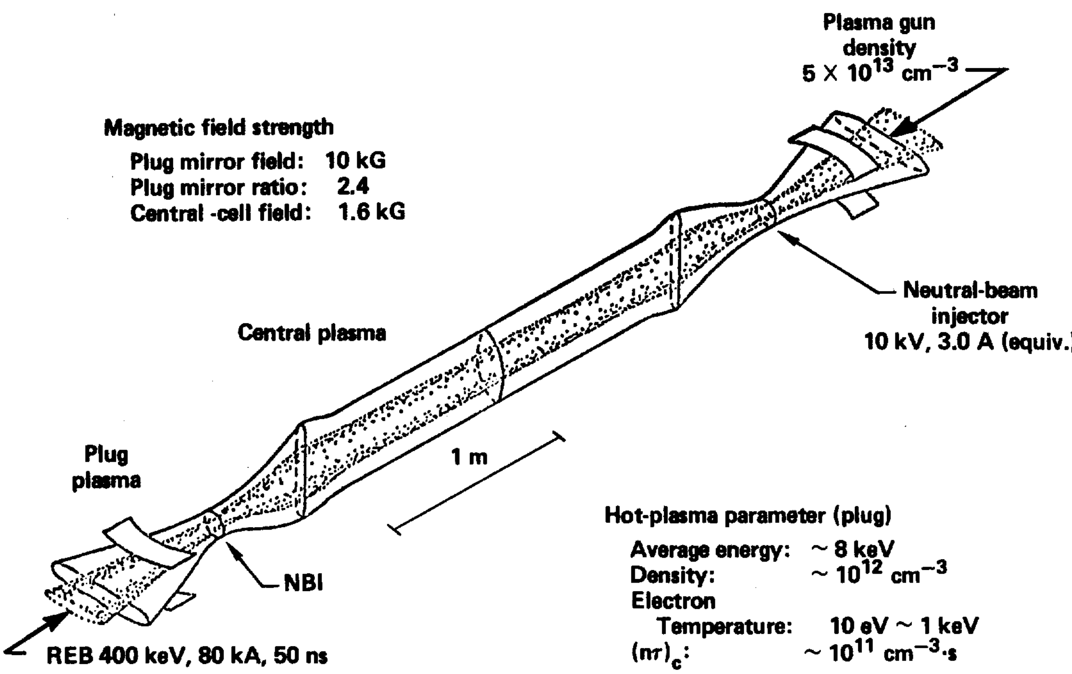

Fig. 4. Schematic diagram of the Gamma 6 plasma (Miyoshi and co-workers, 1978).

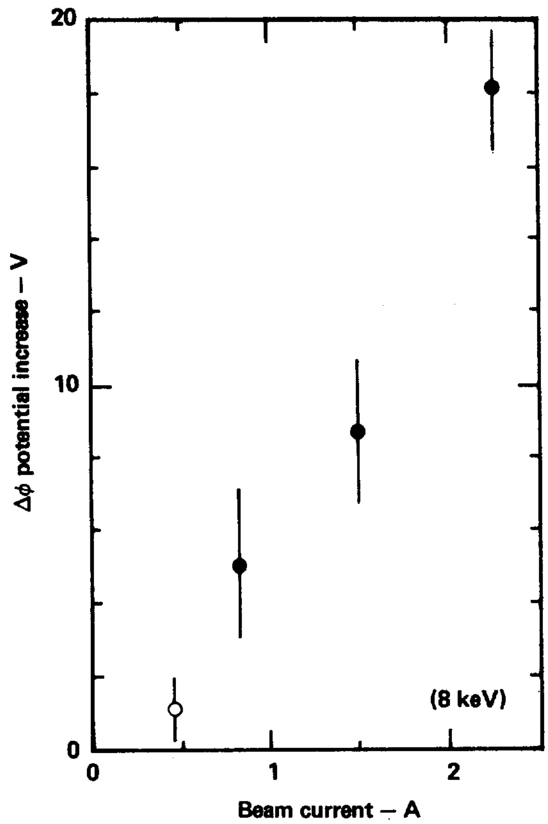

Fig. 5. Gamma 6 results show that the measured potential between the plug and central cell increases with neutral-beam injection current (Miyoshi and co-workers, 1978).

The components of the basic TMX apparatus without the vacuum shell are shown in Fig. 1. The flux tube passing through the middle of the machine is shaped by the end-plug magnets, the transition magnets, and the solenoid set. The end plugs are heated by neutral-beam modules arranged in four clusters, two clusters per plug. A photograph of the TMX apparatus is shown in Fig. 6. The end tanks provide the vacuum enclosure for the plug magnets and house the pumping surfaces for the scattered gas. The center-cell tank completes the vacuum enclosure and, because of its smaller size, provides for easier diagnostic access to the plasma. The scale of the apparatus is set by the end plugs, which are roughly the size of 2XIIB. The central-cell parameters are derived from the plug parameters.

Operation of TMX has just begun at this writing. Measured plug parameters are similar to those observed in 2XIIB for the same injected neutral-beam current. As was true with 2XIIB, TMX parameters are improving with continued operation and with increasing neutral-beam current. Table 3 lists parameters achieved in the first 2 weeks of operation.

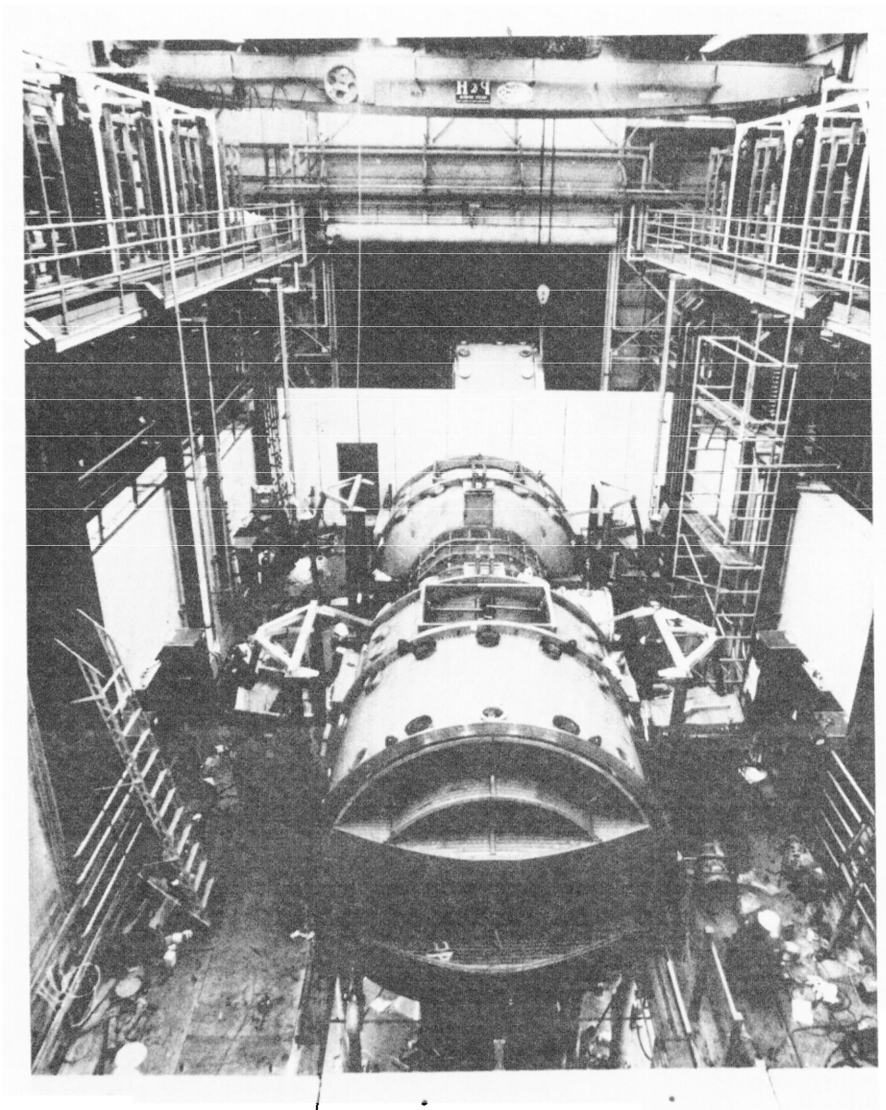

Fig. 6. View of TMX during construction.

TABLE 3 Measured Initial TMX Plasma Parameters

Parameter	Value
Total neutral-beam current (A)	300
End plug density (10^{13} cm^{-3})	2
End plug beta (%)	15
End plug electron temperature (eV)	160
Solenoid density (10^{12} cm^{-3})	2
Solenoid beta (%)	5

The following observations are encouraging:

- Achievement of 5% beta in the solenoid, which indicates the absence of violent magnetohydrodynamic (MHD) instabilities. Plug betas are 5 to 15%.

- Establishment of a tandem mirror longitudinal density profile with center gas feed for the full beam duration of 25 ms.

- Achievement of a 160-eV electron temperature. This is slightly higher than attained in 2XIIB when it was operated with twice the neutral-beam power now attainable in TMX. Furthermore, the lesser amount of TMX power sustains two end plugs, rather than one end plug, and a solenoid volume of 1,000 litres.

Experiments are now in progress in the following areas:

- Increasing the beam current and energy to further improve TMX plasma parameters.

- Learning to optimize methods of feeding gas to the solenoid.

- Determining solenoid confinement properties.

- Performing detailed diagnostic measurements of plasma properties.

In the future, experiments will be carried out on TMX with electron-beam startup, neutral-beam heating of the solenoid, ECRH heating of the end plugs, and thermal barriers.

FIELD-REVERSAL CONCEPTS

The field-reversed mirror (FRM) utilizes the magnetic fields generated by plasma currents to close magnetic field lines within the plasma. The FRM combines some good features of the mirror machine with good features of toroidal systems. The magnets would have the technological simplicity of a linear mirror system with coil windings that do not link the plasma. Plasma confinement would be improved relative to open-field-line mirror confinement because of formation of toroidal closed field line surfaces by plasma currents. There are particular advantages to a FRM with poloidal field only, although it is possible to include a toroidal field as in the Spheromak concept (Bussac, Furth, and Rosenbluth, 1978). To date, the only FRM reactor studies have assumed that the toroidal field is zero. The plasma beta $\beta = [8\pi(T_i + T_e)]/B^2_{vac}$ is then necessarily of order unity. Such a system is theoretically unstable to ideal MHD modes (Barnes and Seyler, 1978). Stability is assumed to be provided by finite Larmor radius effects, although there have been no detailed theoretical calculations. The critical issue is how large a plasma will be stable since the ratio of plasma minor radius to ion gyroradius must be about five to achieve a reactor Q value of five. For these small-size plasmas, one reactor concept (Moir and co-workers, 1977) utilizes a stationary linear chain of 10 field-reversed cells producing a net power output around 100 MW. Systems employing moving field-reversed rings have also been suggested (Fleischmann and Kammash, 1975; Smith and co-workers, 1979). If it turns out that a toroidal field is required for stability, then these reactor concepts would have to be re-evaluated.

Field-Reversal Experiments

There have been no field-reversal experiments with plasmas close to thermonuclear conditions. All experiments have either been at low temperature or density or, as in the case of 2XIIB experiment (Clauser and co-workers, 1978), did not achieve closure of the magnetic field lines. There are, however, a number of field-reversal experiments which have generated the field-reversed configuration. This section reviews results from those experiments, which are listed in Table 4. We shall not discuss either large-aspect-ratio experiments such as the toroidal reversed-field pinch (Baker and co-workers, 1978) or those with a strong toroidal field (Mohri and co-workers, 1978).

TABLE 4 Summary of Present Field-Reversal Experiments

	Plasma ring		Electron ring	Cusp-injected electron beam	Ion ring	
Experiment	LLL-Beta II	LASL-FRX/ Kurchatov	RECE-Christa	NRL/Irvine	NRL	Cornell IREX
Method of generation	Plasma gun	Theta pinch	Relativistic electron beam		Ion diode	
Magnetic field (kG)	5	7/12	0.5	1.8	15	10
Ion energy	2500 eV	350/100 eV	--	--	0.4 MeV	0.5 MeV
Electron energy	600 eV	100	2.5 MeV	1.2 MeV	--	--
Duration (μs)	*	30/100	1000	18	1.25	*

*Has not yet achieved field reversal.

Most closely related to the concept being pursued at Livermore are the plasma ring experiments using plasma guns (Alfvén, Lindberg, and Mitlid, 1960; Jones and Miller, 1968; Turner, 1970) and the reversed-field theta pinches (Eberhagen and Grossman, 1971; Linford, Platts, and Sherwood, 1978; Es'kov and co-workers, 1978). At Livermore, we are building a larger scale version of a magnetized coaxial plasma gun (Alfvén, Lindberg, and Mitlid, 1960) utilizing the high-energy coaxial gun technology developed at LASL (Hennins and Hammel, 1977). The experiments will be carried out on the Beta II machine (modified 2XIIB). Reversed-field theta pinch experiments at Los Alamos (Linford, Platts, and Sherwood, 1978) and Kurchatov (Es'kov and co-workers, 1978) have generated energetic field-reversed plasma several gyroradii in size which exhibit long-time MHD stability.

Field-reversed electron rings have been created by trapping relativistic electron beams. In their experiments, Tuszewski and co-workers (1978) have shown 1-ms electron ring stability and explored many features of the field-reversed configuration. Experiments at NRL (Sethian and co-workers, 1978a, 1978b) and Irvine (Roberson, 1977) show other methods of creating magnetic field reversal using rotating relativistic electron beams. Ion ring field-reversal experiments were initiated at NRL (Kapetanakos and co-workers, 1979) and Cornell (Hammer and co-workers, 1978) following the recent development of intense pulsed ion beams. These experiments can be expected to achieve most impressive plasma parameters as ion beam generator output power increases.

Beta II Plasma Gun

The goal of the experimental program at LLL is to develop means of heating and sustaining field-reversed plasma in a mirror machine with neutral-beam injection. The most difficult step facing this program is startup of the field-reversed configuration. The present plan is to combine recent work on the development of large coaxial plasma guns (Hennins and Hammel, 1977) with the techniques of earlier experiments on production (Alfvén, Lindberg, and Mitlid (1960), transport, and mirror trapping of field-reversed rings (Jones and Miller, 1968; Turner, 1970; Tuszewski and co-workers, 1978). The adaptation of plasma guns for this purpose is being carried out in a joint program at LLL (Simonen, 1978) and LASL (Armstrong and co-workers, 1978), with experimental facilities being constructed at both laboratories.

Schematic diagrams illustrating the basic ideas of the field-reversed plasma gun experiment are shown in Figs. 7 and 8. As shown in Fig. 7 a coaxial plasma gun is fitted with solenoids on the inner and outer electrodes and immersed in an equilibrium guide field. The coil configuration forms a magnetic cusp in front of the gun. Field lines emerging from the inner electrode generate a strong radial magnetic field component at the gun exit. Return flux from the inner electrode is controlled by the outer electrode solenoid, so that the gun can be operated with a bias field or very low field between the electrodes. Gas is puffed into the region between the electrodes at a distance halfway between the breech and the muzzle. After a suitable delay, a capacitor bank is discharged between electrodes, creating a radial current sheet near the gas inlet. The current sheet is pushed down the gun barrel by the $j \times B$ hydrodynamic force. High-beta plasma reaching the end of the gun pushes the field lines out until eventually they become highly elongated and then reconnect so that a drifting field-reversed plasma ring is formed. Because the plasma mixes with the azimuthal field in the gun, we expect the rings to trap some toroidal field as well as a poloidal field; this may be beneficial for stability. The field-reversed plasma formation scheme shown in Fig. 7 was, as far as we know, first outlined by Alfvén (1958) and then demonstrated to work by Alfvén, Lindberg, and Mitlid (1960). After the ring is formed, the sequence continues in Fig. 8. The ring drifts along the equilibrium field until it is reflected by a barrier field and trapped by a fast-rising gate field.

Mirror reflection and trapping of a field-reversed ring having a total energy of a few joules has been achieved by Jones and Miller (1968). We wish to extend this technique in Beta II to rings having several kilojoules total energy. The ring is then heated and sustained by neutral-beam injection.

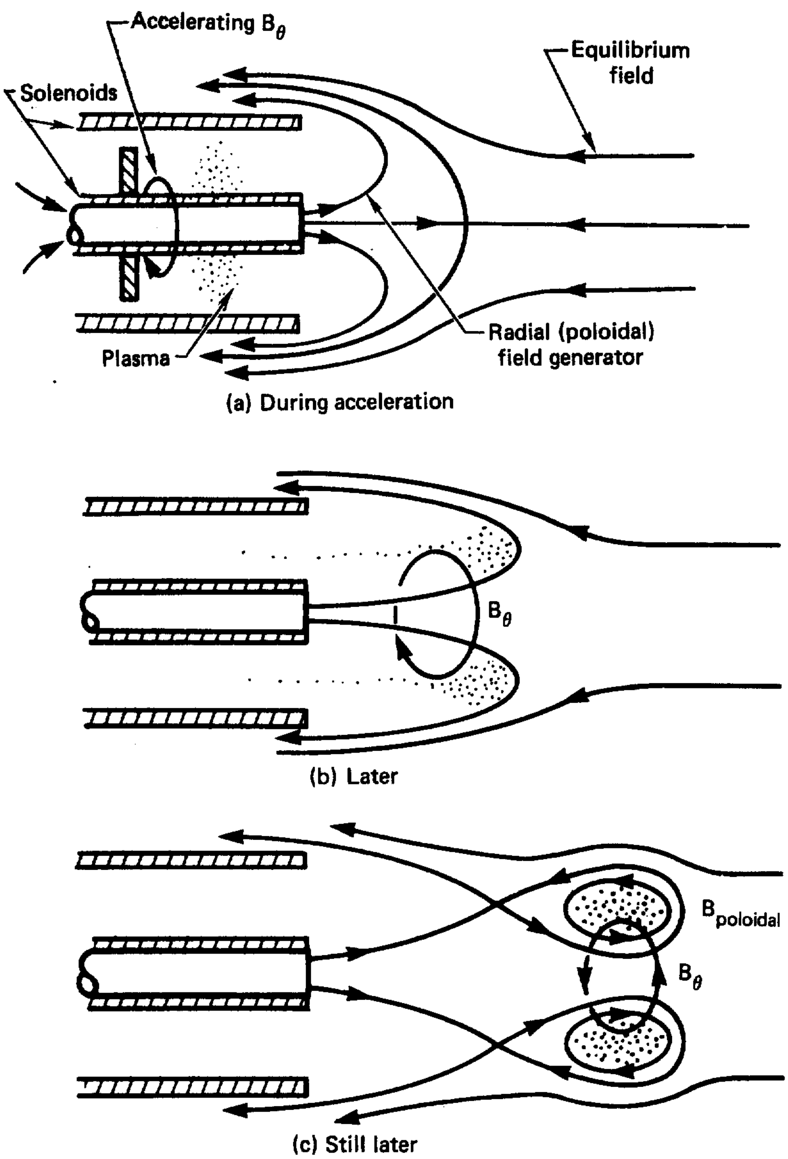

Fig. 7. Schematic of plasma gun formation of field-reversed plasma.

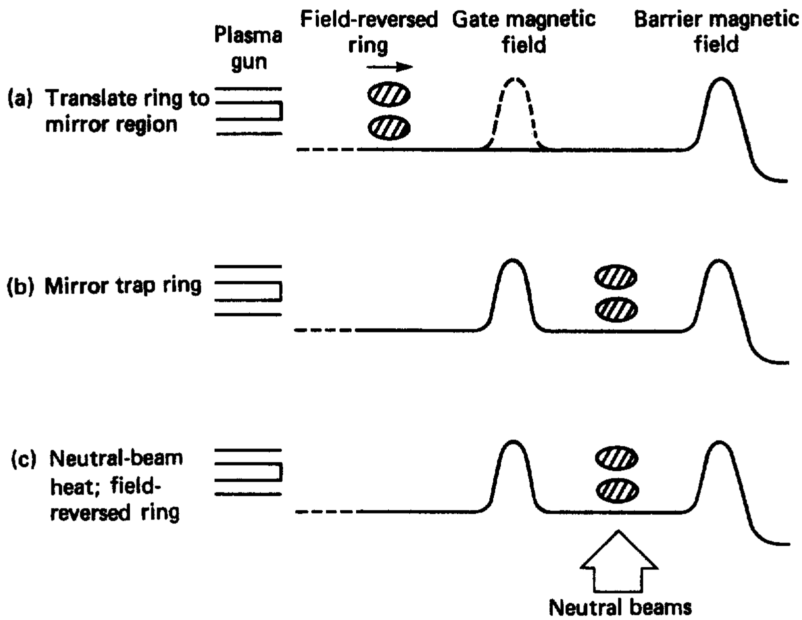

Fig. 8. Translation, mirror trapping, and neutral-beam heating of field-reversed rings.

The initial experimental goal is to produce and diagnose field-reversed rings with parameters that are compatible with heating and sustaining by the ten Lawrence Berkeley Laboratory (LBL) 20-kV, 50-A neutral-beam injectors installed on Beta II (injected beam power ≈5 MW, vacuum magnetic field strength ≈5.0 kG). For this, the total energy of the plasma ring should be several kilojoules occupying a plasma volume of several litres. The field-reversal parameter $\Delta B/B_{vac}$ should be approximately 2, so that the field at the ring center is equal in magnitude and opposite to the applied field. The total trapped poloidal flux ϕ should roughly equal $1.5 \times 10^3 \mathrm{kG \cdot cm^2}$ for a 5.0-kG vacuum field. In this way, the desired field configuration is created in the target plasma and the neutral beams are used to heat and supply particles but not to build up the field-reversed flux. A mean target plasma ring density $n \approx 3 \times 10^{14} \mathrm{cm^{-3}}$ would be well matched to beam injection, absorbing most of the incident beam energy while allowing the beam atoms to penetrate to the interior of the ring.

Once the rings are formed, they must be stopped. If this is to be done with a magnetic mirror, the required mirror ratio R_m is a sensitive function of the ratio of translation kinetic energy of the rings U_k to the sum of their thermal energy U_p and magnetic energy U_B. For a spherical Hill vortex equilibrium (Shafranov, 1958), it can be shown that this ratio of energies is related to the mirror ratio by

$$\frac{U_k}{U_p + U_B} = \sqrt{R_m} - 1 \quad .$$

Thus, for $0.5 < U_k/(U_p + U_B) < 1.0$, R_m falls in the range 2.25 to 4.0. After formation of the field-reversed rings, important tasks will be to determine the mirror ratio required to stop the rings and the extent of our control over the ratio of translational to thermal and magnetic energy.

Once the rings have been stopped, the critical question is the energy confinement time required so that they can be heated and sustained by neutral-beam injection. For a plasma ring energy of several kilojoules and the 5-MW of neutral-beam power available on Beta II, the required confinement time is of the order of a millisecond.

A schematic of the plasma gun constructed to test the ideas just described is shown in Fig. 9. The design very closely follows that developed at Los Alamos Scientific Laboratory (LASL) (Hennins and Hammel, 1978; Marshall and Hennins, 1965), with adaptations required by the addition of the solenoid coils on the inner and outer solenoids. Some of the physical parameters of this gun are summarized in Table 5.

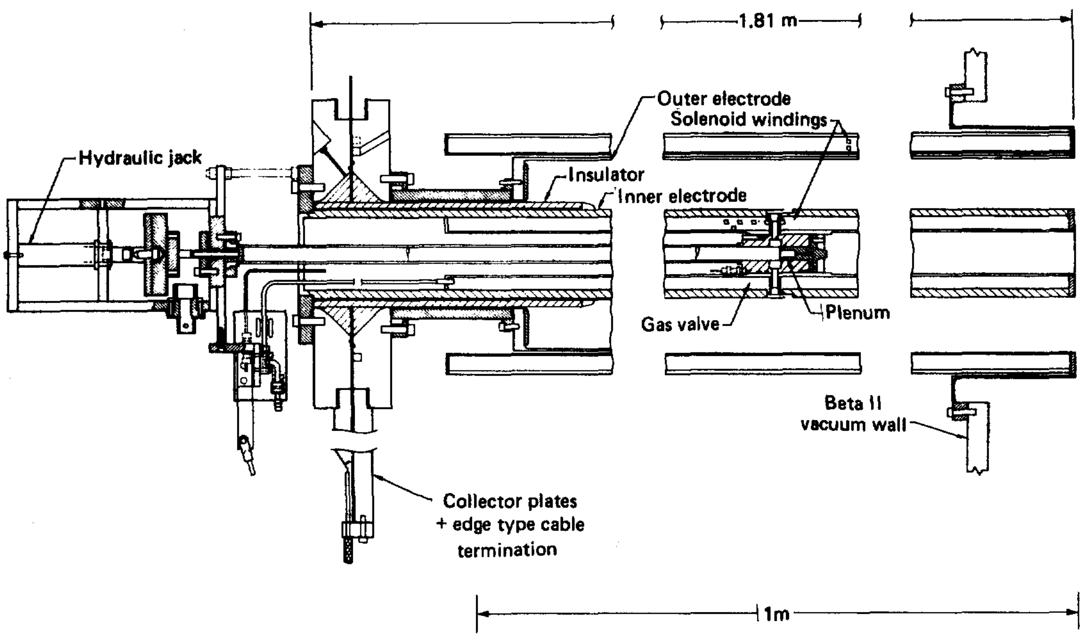

Fig. 9. Diagram of Beta II plasma gun.

Data taken with a coaxial plasma gun similar to that shown in Fig. 9 but without the solenoid coils have been reported by Hennins and Hammel (1977) at LASL. The data demonstrated plasma-gun production of multi-keV ions in sufficient quantity to form the field-reversed target for neutral-beam injection. A fast-plasma component was observed with D^+ velocities between 3×10^7 and 8.9×10^7 cm/s and having a mean energy $E \approx 3.0$ keV. The transverse energy of the plasma target 150 cm from the gun was 6.5 kJ, and the total energy measured on a calorimeter behind a 10-kG solenoid was W = 35 kJ. From this, we estimate the number of D^+ ions in the fast-plasma component $N \approx W/E \approx 7 \times 10^{19}$. Roughly, this energy and particle output are an order of magnitude greater than is needed for the field-reversed rings in Beta II, allowing a margin for inefficiency in transmission through the magnetic cusp. The total number $N \approx 7 \times 10^{19}$ of D^+ ions estimated to be in the fast-plasma component amounts to only about 3% of the total

TABLE 5 Field-Reversed Plasma Gun Parameters

Parameter	Value
Plasma gun:	
Inner electrode diameter	15 cm
Outer electrode diameter	30 cm
Electrode length	150 cm
Plenum volume	3.0 cm^3
Inner electrode wall	1.3 cm SS + 0.10 cm Cu
Outer electrode wall	0.32 cm SS
Capacitor bank:	
Capacitance	232 μF
Voltage	40 kV
Inner solenoid:	
No. of turns	133
Mean turns radius	5.2 cm
Inductance	120 μH
Resistance	22 mΩ
Magnetic field	$\leq$40 kG
Outer solenoid:	
No. of turns	133
Mean turns radius	18.8 cm
Inductance	1.6 mH
Resistance	80 mΩ
Magnetic field	$\leq$6 kG
Guide field	$\leq$6 kG

50 atm·cm^3 of gas puffed into the plenum chamber. Cold, slow plasma may be expected to flow out of the gun after the fast plasma has passed. The cusp field should prevent this plasma from coming into contact with the plasma ring by diverting it onto a wall, where it will recombine to form gas. For experiments lasting up to a few milliseconds, this gas will not be troublesome, but beyond that it will diffuse to the hot plasma and cause excessive charge-exchange loss and plasma cooling. Eventually then, means must be devised for either pumping this gas or improving the gas efficiency of coaxial guns.

Reversed-Field Theta Pinch Experiments

Interest was renewed in reversed-field theta pinch experiments following the discovery of long-time equilibrium (Eberhagen and Grossman, 1971; Linford, Platts, and Sherwood, 1978; Es'kov and co-workers, 1978). These experiments have burned through the radiation barrier to reach hundreds of eV energy and remain stable for many MHD transit times. The enhanced confinement and high temperatures compared to open-ended theta pinches are attributed to the closed magnetic field lines.

The reversed-field theta pinch configuration in the LASL-FRX (Linford, Platts, and Sherwood, 1978) experiments is terminated by the growth of a rotational $m = 2$ instability. According to Linford, the rotation develops when a substantial amount of plasma and flux has been lost, and the loss of plasma may be the cause rather than the effect of the rotational instability. There is hope then that if the confinement of plasma and flux can be improved in larger experiments, this $m = 2$ mode will not be a limiting factor. FRX reversed-field theta pinch experiments during the stable period are of considerable interest since these experiments operate in the finite gyroradius range $3 < a/\rho_i < 10$ of interest for field-reversed mirror reactors. The confinement time during the equilibrium phase is about 40 to 80 μs, which exceeds the Bohm time but is shorter than the 300-μs classical time if we assume that the estimate of $T_e = 100$ eV is accurate. In Linford's experiments, there is evidence indicating improved confinement time with increase of the minor radius of the ring, i.e., with a/ρ_i.

Reversed-field theta pinch experiments carried out in the Soviet Union (Es'kov and co-workers, 1978) show stable confinement for up to 100 μs limited only by the crowbarred magnet decay time. The $m = 2$ rotational instability has never been observed in these experiments, perhaps because cusp magnetic mirrors are used at the ends and fast-pulsed gating coils force reconnection at a precisely controllable time. The forced reconnection induces a strong axial shock wave which heats the plasma and compresses it against the wall so that the ratio of separatrix radius to wall radius is typically $r_s/r_w \approx 0.7$ to 0.8. For comparison, in the experiments of Linford, Platts, and Sherwood (1978), $r_s/r_w \approx 0.5$. For $r_s/r_w \leq 0.3$, the Soviet experimenters observe a variety of unstable and short-lived plasma behavior such as violent disruption and tearing of the neutral current sheet, rapid loss of flux, and growth of an $m = 4$ nonrotating distortion of the plasma cylinder. Aside from development of cusp-mirror end geometry and forced reconnection coils, a Soviet group has also developed a pulsed octupole barrier field to keep the neutral current sheet away from the wall during reversal of the applied field. This results in improved flux trapping, plasma purity, and absence of tearing instability.

In summary, reversed-field theta pinch experiments provide information not presently available from other devices on stability and confinement properties at parameters relevant to field-reversed mirrors.

TANDEM MIRROR AND FIELD-REVERSED MIRROR EXPERIMENTS

FIELD-REVERSED ELECTRON-RING EXPERIMENTS

The RECE-Christa Experiment

The RECE-Christa experiment at Cornell University (Tuszewski and co-workers, 1978) employs a relativistic electron generator to produce field-reversed electron ring configurations. Although high-energy proton rings will be needed for reactor applications, the electron-ring experiments are being performed to investigate various characteristics of field-reversed, large-orbit configurations with lower cost and simpler technology. This series of experiments has been successful in examining a number of important issues:

- Production of strong field reversal with field reversal lasting for 1.1 ms;
- Compression of electron rings by a factor of 3 with no anomalous losses;
- Transport of electron ring with only small losses;
- Discovery of quadrupole-induced resonance losses.

Rotating Electron Beam Field-Reversal Experiments

A second method of generating reversed magnetic fields is by the use of a rotating relativistic electron beam. Such experiments have been carried out at the Naval Research Laboratory (NRL) (Sethian and co-workers, 1978a, 1978b) and at the University of California at Irvine (Roberson, 1977). In the NRL experiments, the beam is injected into gas; the Irvine experimenters have used gas and plasma targets. The REB acquires its rotation by passing through a cusp magnetic field. The azimuthal current generates the reversed poloidal field configuration, and the longitudinal current provides a toroidal field. The field-reversed structure is maintained by induced plasma currents rather than by trapped beam electrons as in the RECE-Christa experiments.

ION-RING FIELD-REVERSAL EXPERIMENTS

The invention of high-current reflex ion generators allows field-reversal experiments using high-energy, large-orbit ions. Such experiments are underway at NRL (Kapetanakos and co-workers, 1979) and at Cornell University (Hammer and co-workers, 1978).

The NRL experiment employs a 200-kA, 1.4-MeV, 50-ns hollow proton beam. Peak proton current reaches 380 kA, with greater than 6×10^{16} protons extracted per pulse. After passing through a cusp magnetic field, the ion ring acquires perpendicular energy. Very recently (Kapetanakos and co-workers, 1979) it has been reported that field reversal has been achieved, the field inside the proton ring reaching a value of 1.25 times the vacuum field of 1.50 kG. In the next stage of the experiment, pulsed coils will trap the field-reversed ion ring within the magnetic mirror.

In an ion-ring experiment at Cornell University, an annular anode magnetically insulated ion diode is used to generate an intense, 500-keV, 100-ns proton beam. This beam will be injected into the IREX machine with a 10-kG magnetic mirror field. Resistive trapping will be employed.

CONCLUSIONS

Tandem mirrors and field-reversed mirrors employ the attributes of single-cell mirror machines but have the possibility of obtaining higher power balance. A number of experiments are underway to address and demonstrate the physics principles behind these devices.

The TMX and AMBAL-1 tandem mirrors are expected to create plasmas near thermonuclear conditions by employing neutral-beam heating of the solenoid. Early TMX results look encouraging. The Gamma 6 tandem mirror has demonstrated several tandem mirror physics principles, and Phaedrus will demonstrate rf heating in a tandem mirror configuration. The field-reversed mirror is somewhat speculative on a theoretical basis; however, experiments are encouraging and possible reactor characteristics are attractive. Experiments are also in progress to investigate field-reversed plasma rings, electron rings, and ion rings.

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